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(54) **OPTICAL METROLOGY SYSTEM FOR SPECTRAL IMAGING OF A SAMPLE**

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(57) **ABSTRACT**

An optical metrology device is capable of detection of any combination of photoluminescence light, specular reflection of broadband light, and scattered light from a line across the width of a sample. The metrology device includes a first light source that produces a first illumination line on the sample. A scanning system may be used to scan an illumination spot across the sample to form the illumination line. A detector spectrally images the photoluminescence light emitted along the illumination line. Additionally, a broadband illumination source may be used to produce a second illumination line on the sample, where the detector spectrally images specular reflection of the broadband illumination along the second illumination line. The detector may also image scattered light from the first illumination line. The illumination lines may be scanned across the sample so that all positions on the sample may be measured.
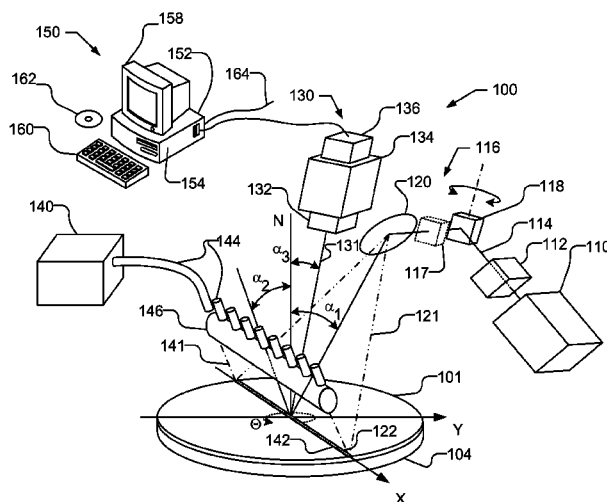
30 Claims, 8 Drawing Sheets

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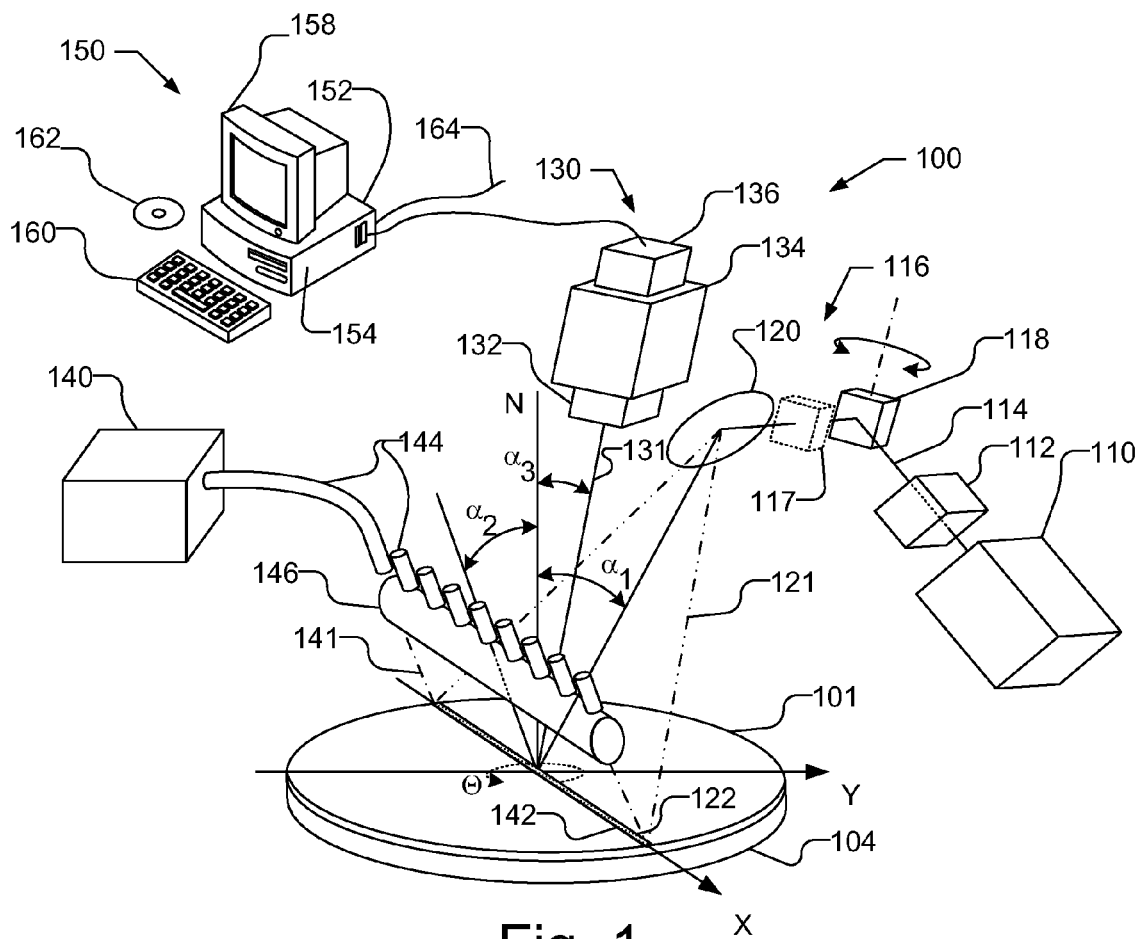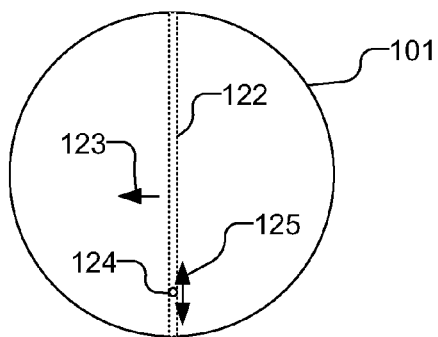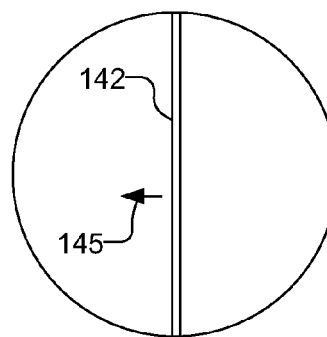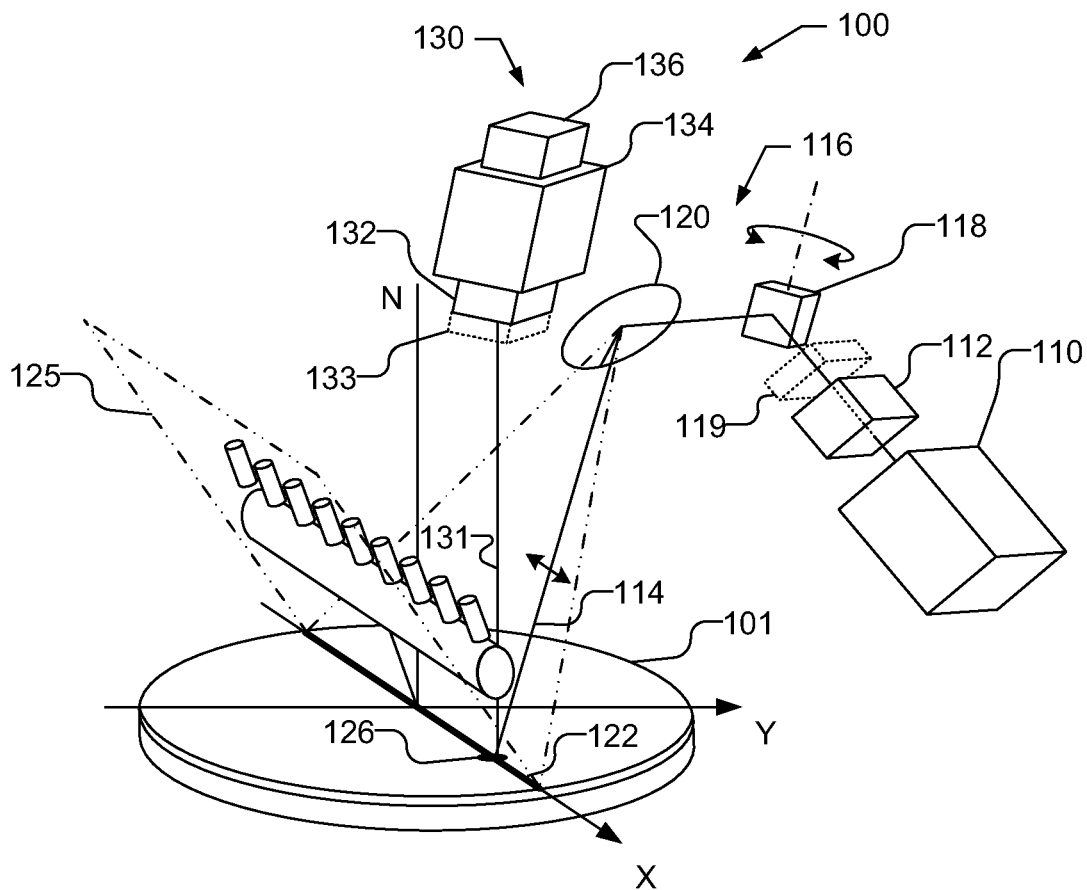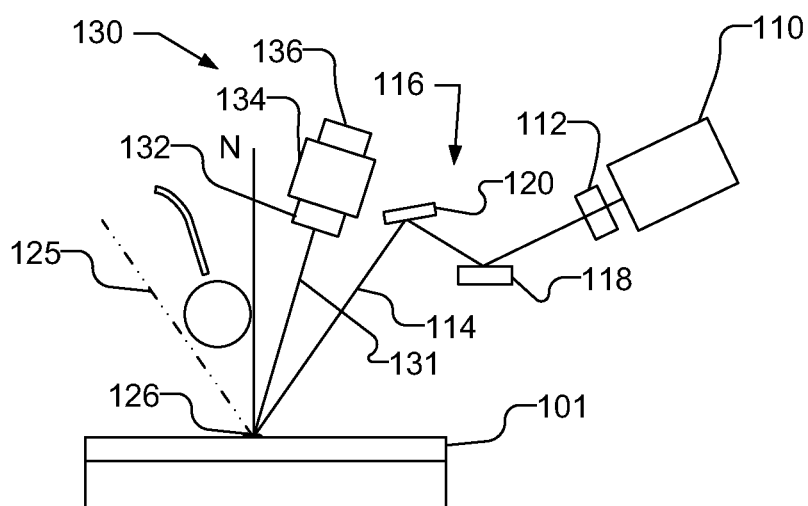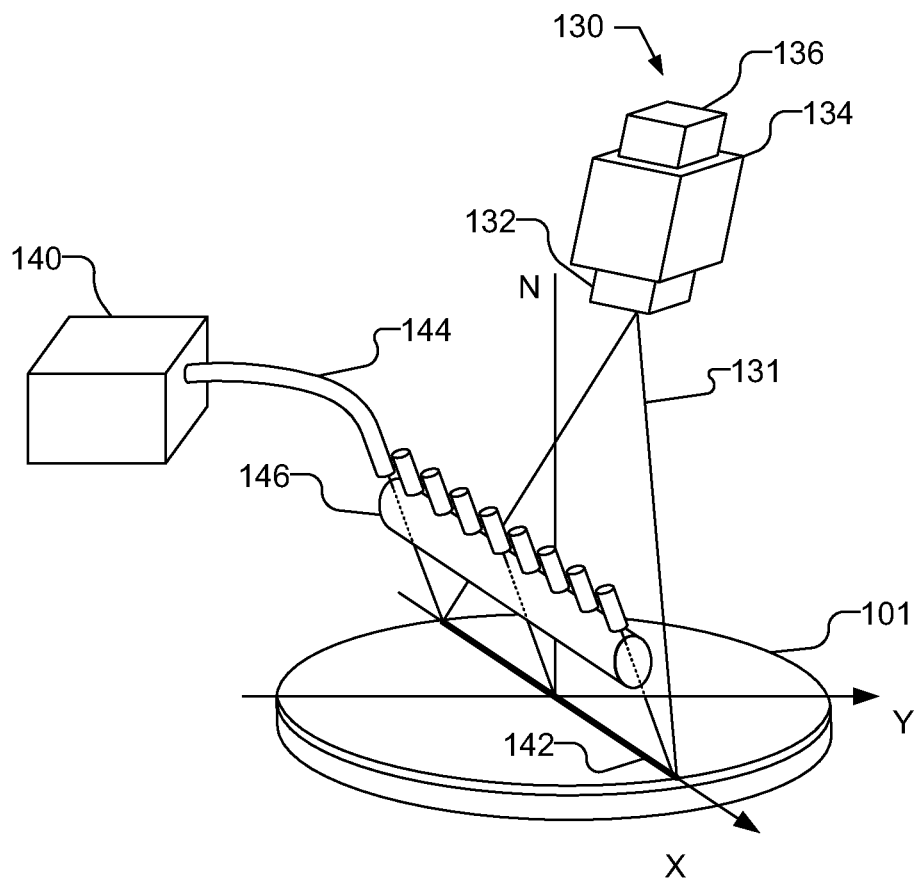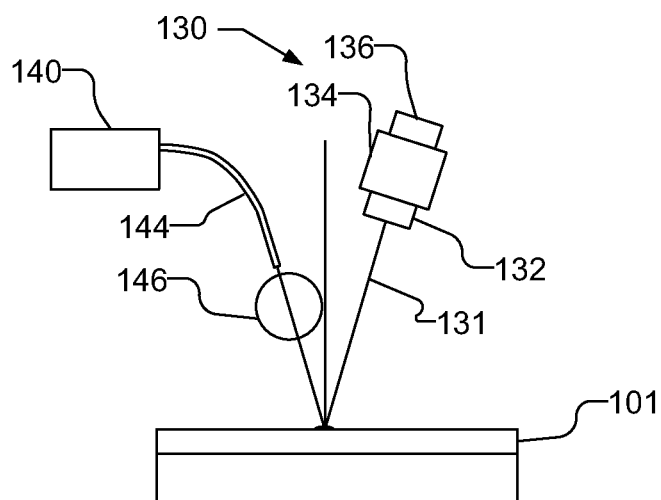
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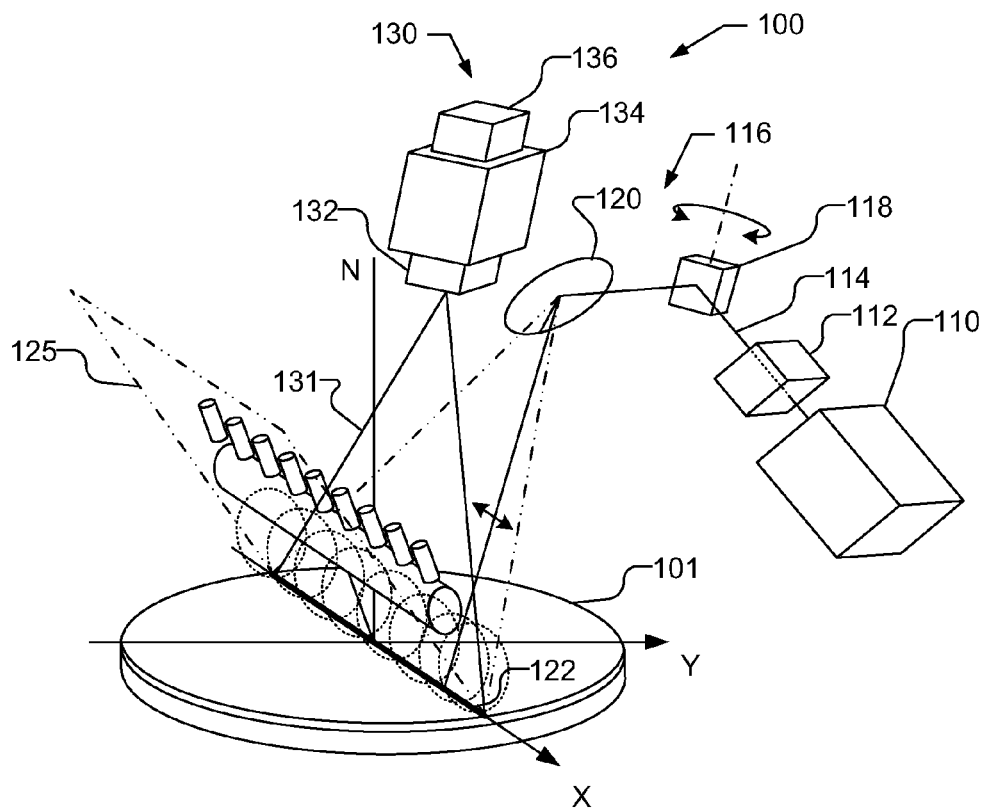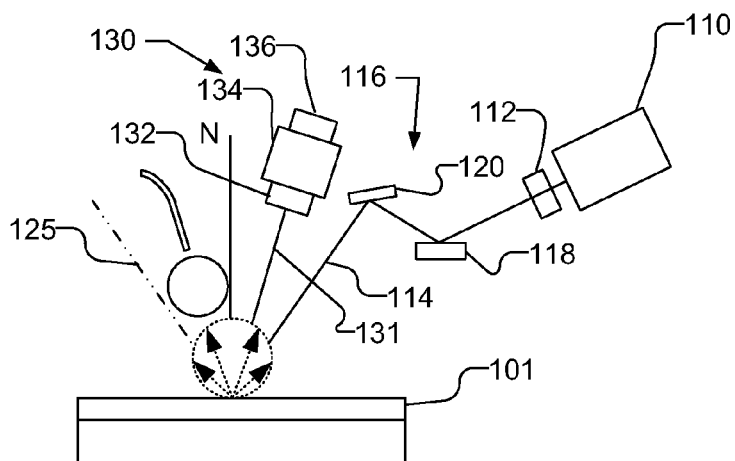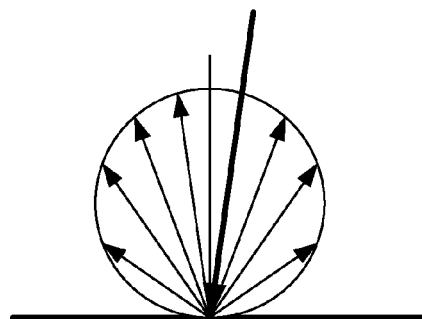
Fig. 1

Fig. 2A

Fig. 2B

Fig. 3A

Fig. 3B

Fig. 4A

Fig. 4B

Fig. 5A

Fig. 5B

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Illuminating a surface of a sample at a first angle of incidence with a first light source along a first illumination line having an orientation in a first direction ⟶302

Illuminating the surface of the sample at a second angle of incidence with a second light source along a second illumination line having an orientation in the first direction and that overlays the first illumination line ⟶304

Detecting the photoluminescence light emitted by the sample along the first illumination line and specular reflection of broadband light from the second illumination line with a two-dimensional array having a first dimension representing spatial information corresponding to position along the first illumination line and the second illumination line and a second dimension representing spectral information ⟶306

Moving the first illumination line and the second illumination line across the surface of the sample in a second direction that is different than the first direction ⟶308

Producing a three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information using detected photoluminescence light and detected specular reflection of broadband light as the first illumination line and the second illumination line are moved across the surface of the sample ⟶310
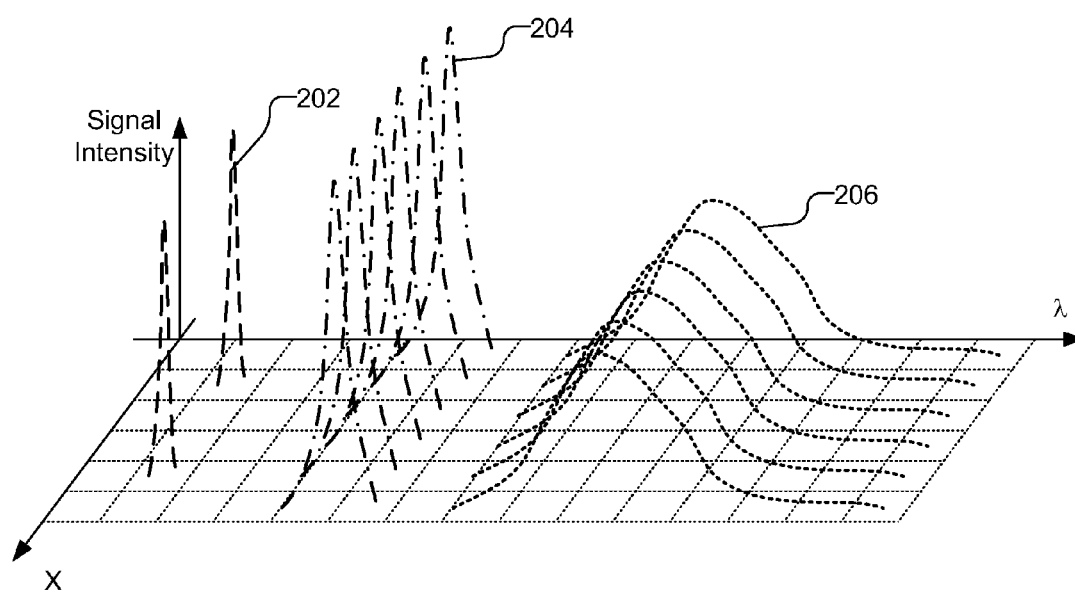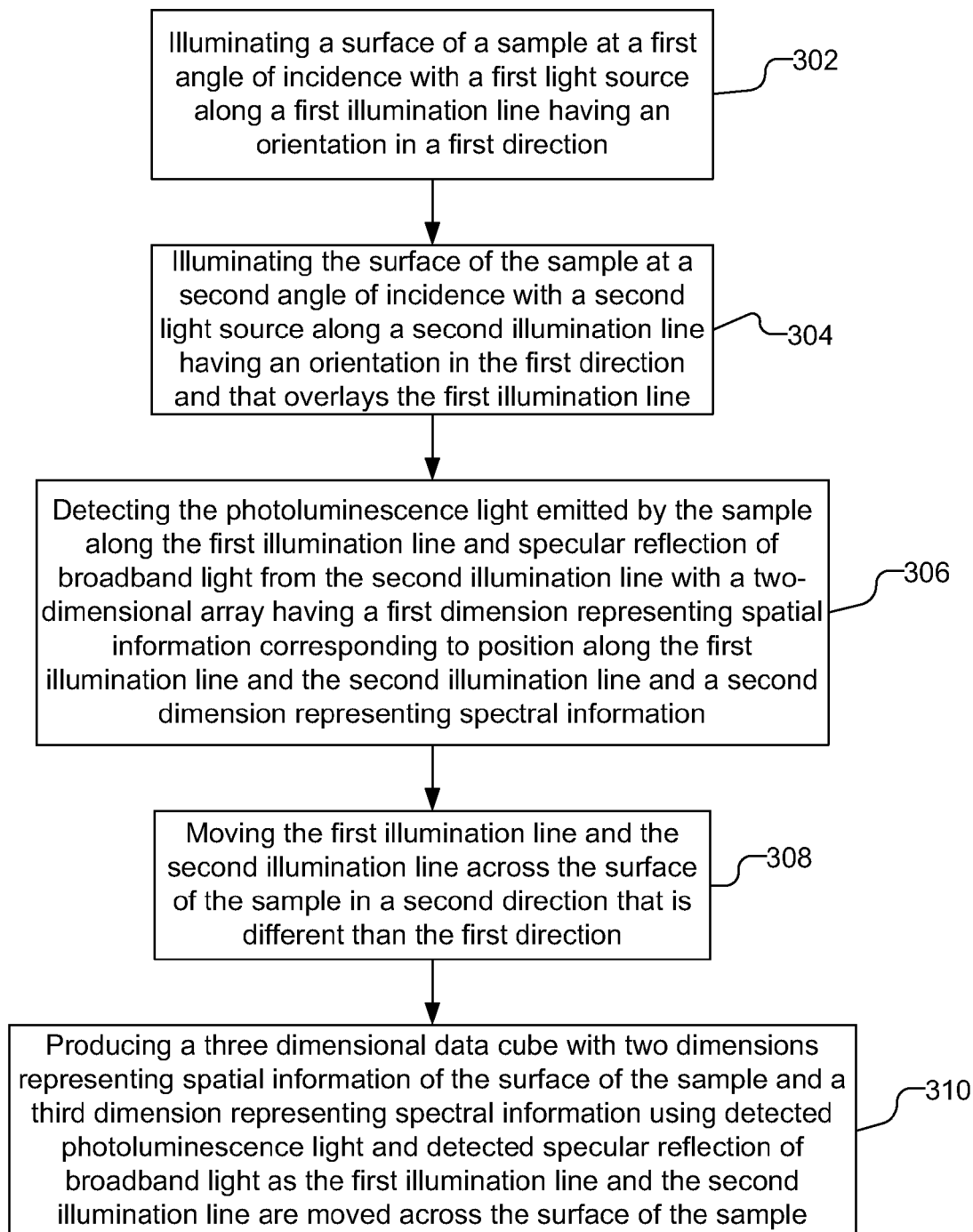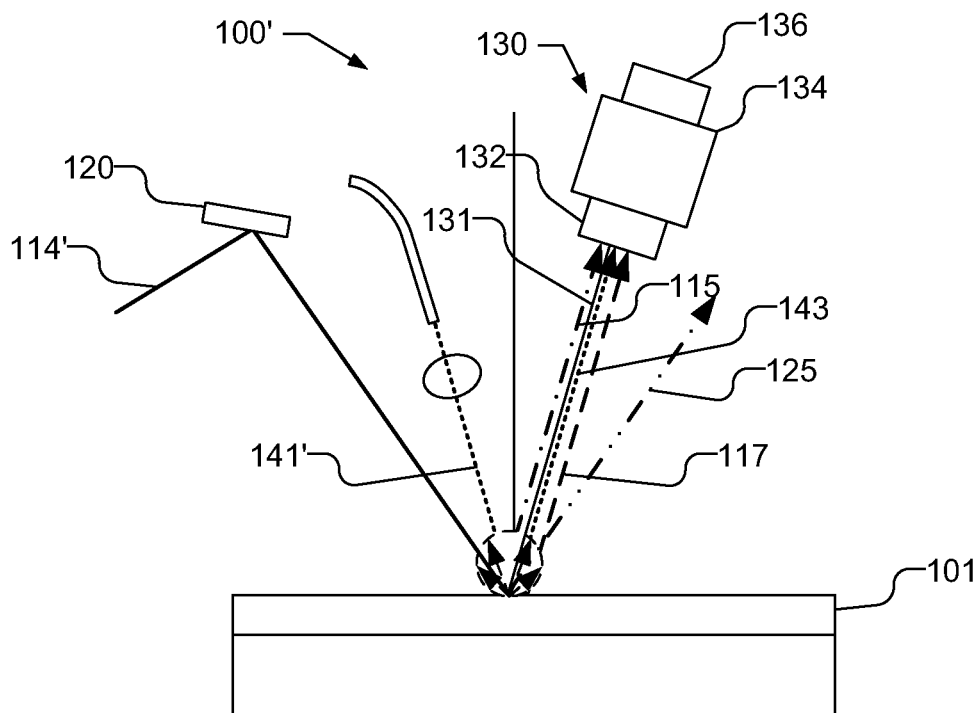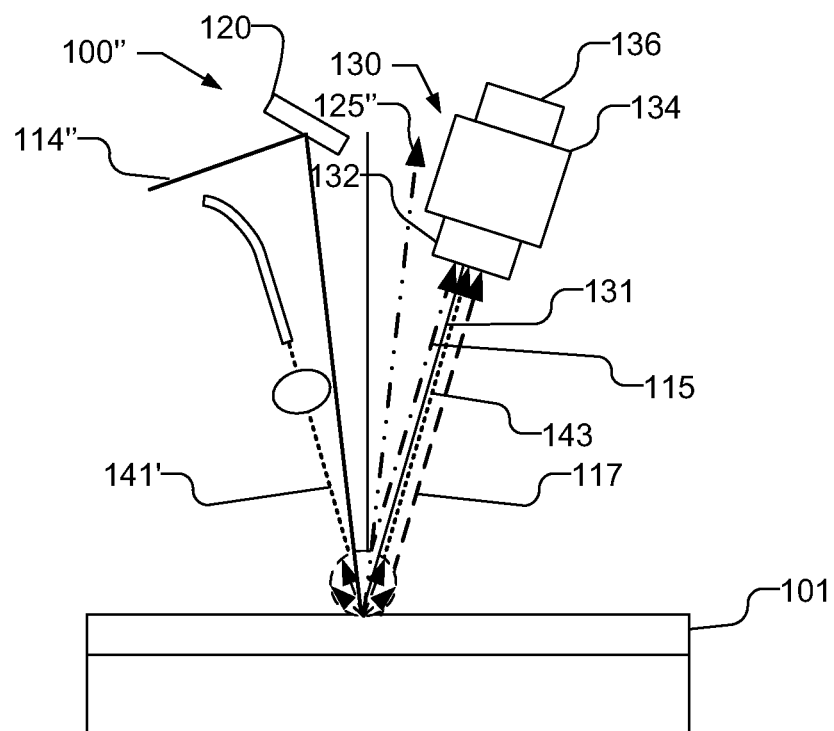
Fig. 10

Fig. 11

Fig. 12

OPTICAL METROLOGY SYSTEM FOR SPECTRAL IMAGING OF A SAMPLE

BACKGROUND

Photoluminescence imaging and spectroscopy is a contactless, nondestructive method of probing the electronic structure of materials, such as silicon semiconductor wafers, solar cells, as well as other workpieces and materials. In a typical photoluminescence process, light is directed onto a wafer or other workpiece (hereinafter collectively referred to as a "sample"), where at least some of the light is absorbed. The absorbed light imparts excess energy into the material via a process of "photo-excitation." The excess energy is dissipated by the sample through a series of pathways; one such pathway is the emission of light, or photoluminescence. The intensity and spectral content of the photoluminescence is directly related to various material properties of the sample and, thus, can be used to determine certain characteristics of the sample, including defects, as discussed in U.S. Pat. No. 7,113,276B1, which is incorporated herein by reference.

Reflectance or reflectivity imaging is a contactless, nondestructive method of probing the surface with a broadband illumination source and analyzing the intensity and spectral content of the signal bounced back from the surface. The surfaces typically can be classified into specular or diffuse surfaces and real objects typically exhibit a mixture of both properties.

It is sometimes desirable, e.g., for semiconductor wafer inspection applications, to measure intensity and spectral content of the photoluminescence and reflectance of the semiconductor wafer-size workpiece for the purpose of quality inspection in the same apparatus either concurrently or in a short sequence, with single wafer load, while achieving a high measurement throughput combined with high measurement spatial and spectral resolution.

Conventionally, spectral photoluminescence or combined spectral photoluminescence and reflectance are measured using a single point-by-point inspection solution. In a point-by-point solution, the sample is placed on an X-Y motion (or R-Θ) system and is illuminated and measured at a single excitation point. The sample is moved to another measurement point and again illuminated and measured. By repeating the translation of the sample in the X-Y directions, a photoluminescence and reflectance maps could be constructed from the point-by-point measurements. This solution, however, is inherently slow and therefore impractical in the full wafer inspection systems, especially at large specimen sizes, close to and above 100 mm in diameter, due to the low throughput.

SUMMARY

An optical metrology device is capable of detection of any combination of photoluminescence light, specular reflection of broadband light, and scattered light from a line across the width of a sample. The metrology device includes a first light source that produces a first illumination line on the sample. A scanning system may be used to scan an illumination spot across the sample to form the illumination line. A detector spectrally images the photoluminescence light emitted along the illumination line. Additionally, a broadband illumination source may be used to produce a second illumination line on the sample, where the detector spectrally images specular reflection of the broadband illumination along the second illumination line. The detector may also image scattered light

from the first illumination line. The illumination lines may be scanned across the sample so that all positions on the sample may be measured.

In one embodiment, an apparatus includes a light source that produces an illumination beam; a optical system that receives the illumination beam and produces an illumination spot on a surface of the sample; a scanning system that scans the illumination spot to form an illumination line across the sample, wherein the scanning system scans the illumination beam in a plane that is at a non-normal angle of incidence on the sample, and wherein the sample emits photoluminescence light in response to excitation caused by the illumination spot along the illumination line; a stage for providing relative movement between the illumination line and the sample; a detector that images the photoluminescence light emitted along the illumination line on a two-dimensional array with a first dimension representing spatial information along the illumination line and a second dimension represent spectral information of the photoluminescence light, wherein the detector produces an image frame representing the photoluminescence light emitted along from the illumination line, and wherein the detector produces a plurality of image frames for the illumination line on the surface of the sample as the stage produces relative movement between the illumination line and the sample; and a processor coupled to the detector to receive the plurality of image frames and generates a photoluminescence image of the surface of the sample.

In one embodiment, an apparatus includes a stage for providing relative movement between the illumination line and the sample in a first direction; a first illumination source that produces a first light beam; a first lens system that causes the first light beam to be incident on a surface of the sample as a first illumination line orientated along a second direction that is different than the first direction, the first illumination line being incident on the sample at a first angle of incidence, wherein the sample emits photoluminescence light in response to excitation caused by the first light beam along the first illumination line; a broadband illumination source that produces broadband light; a second lens system that focuses the broadband light onto the sample as a second illumination line orientated along the second direction and that is overlaid on the first illumination line on the surface of the sample, the broadband light being incident on the sample at a second angle of incidence that is different than the first angle of incidence; a detector that receives reflected broadband light from the surface of the sample from the second illumination line and receives the photoluminescence light emitted by the sample along the first illumination line, wherein the detector images the reflected broadband light and the photoluminescence light on a two-dimensional array with a first dimension representing spatial information along the second direction and a second dimension representing spectral information of the reflected broadband light and the photoluminescence light and produces an image frame in response, wherein the detector produces a plurality of image frames for a plurality of positions of the first illumination line and the second illumination line that are overlaid on the surface of the sample as the stage moves the sample in the first direction; and a processor coupled to the detector to receive the plurality of image frames and stores the plurality of image frames as a three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information.

In one embodiment, a method includes illuminating a surface of a sample at a first angle of incidence with a first light source along a first illumination line having an orientation in a first direction, wherein the sample emits photolumines-

cence light from the first illumination line in response to excitation caused by light from the first light source; illuminating the surface of the sample at a second angle of incidence with a second light source along a second illumination line having an orientation in the first direction and that overlays the first illumination line, wherein the second angle of incidence is different than the first angle of incidence, and wherein the second light source is a broadband light source, wherein broadband light is reflected from the surface of the sample; detecting the photoluminescence light emitted by the sample along the first illumination line and specular reflection of broadband light from the second illumination line with a two-dimensional array having a first dimension representing spatial information corresponding to position along the first illumination line and the second illumination line and a second dimension representing spectral information; moving the first illumination line and the second illumination line across the surface of the sample in a second direction that is different than the first direction; and producing a three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information using detected photoluminescence light and detected specular reflection of broadband light as the first illumination line and the second illumination line are moved across the surface of the sample.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an optical metrology device capable of simultaneous detection of any combination of photoluminescence light, specular reflection of broadband light, and scattered light from a line across the width of a sample.

FIG. 2A illustrates a top view of the surface of the sample with an illumination spot from a first light source that is scanned across the width of the sample to produce an illumination line and the illumination line is moved across the sample.

FIG. 2B illustrates a top view of the sample with the illumination line from a second light source and the illumination line is moved across the sample.

FIGS. 3A and 3B illustrate a perspective view and side view, respectively, of a dark channel observation of scattered light by the optical metrology device of FIG. 1.

FIGS. 4A and 4B illustrate a perspective view and side view, respectively, of the bright field reflectance observation by the optical metrology device of FIG. 1, with a narrow band light source and associated optics omitted for clarity.

FIGS. 5A and 5B illustrate a perspective view and side view, respectively, of the excitation of the sample with the scanning illumination beam and the emitted photoluminescence light collection by the optical metrology device of FIG. 1.

FIG. 6 illustrates an incident illumination beam and the Lambertian characteristic of the emitted photoluminescence light.

FIGS. 7 and 8 illustrate a side view (along the Y-Z plane) and a front view (along the X-Z plane), respectively, illustrating the simultaneous collection of dark field scattered radiation, bright field reflectance radiation and photoluminescence light by the optical metrology device of FIG. 1.

FIG. 9 illustrates the signal separation of the three spectral channels (dark field scattered radiation, bright field reflectance radiation, and photoluminescence light) imaged by a 2D sensor array.

FIG. 10 is a flow chart illustrating a method of optical metrology data from a number of light sources.

FIGS. 11 and 12 illustrate side views (along the Y-Z plane) of alternative configurations of the optical metrology device from FIG. 1.

DETAILED DESCRIPTION

FIG. 1 illustrates an optical metrology device 100 capable of simultaneous detection of any combination of photoluminescence light, specular reflection of broadband light, and scattered light from a line across the width of a sample. The sample is moved in a single direction to sweep the line across the sample so that data may be quickly collected from every position on the surface of the sample.

The metrology device 100 includes a first light source 110, which may be, e.g., a narrow band illumination source, such as a laser. By way of example, the light source 110 may be a high intensity laser, such as a Continuous Wave (CW) laser with peak wavelength at 405 nm and power in 1 mW to 500 mW range, depending on the photoluminescence efficiency of the measured sample and desired signal intensity to be recorded by the detector. If desired, more than one laser may be used to produce multiple narrow band wavelengths that are combined for light source 110. By way of example, other laser wavelengths, such as 266 nm, 355 nm, 375 nm, 532 nm, 640 nm or 830 nm, and others not listed here, may additionally or alternatively be used, either individually or selectively combined. Laser(s) used as light source 110 may operate either in Continuous Wave or Q-Switched mode of operation. If the Q-Switched (QS) laser is used for sample excitation, the instantaneous power, i.e. power during the pulse, may be much higher, e.g., in a few (2.5 kW) kilowatt range.

A lens system including optics 112 is used to produce an illumination spot with the illumination beam 114 on the surface of the sample 101. The illumination spot produced by the illumination beam 114 should have a size and/or power density to excite photoluminescence in the sample 101. By way of example, the illumination spot size may be between 50 μm to 1 mm range and/or have a power density of between approximately 0.1 W/cm^2 to 10^8 W/cm^2 range. For example, if a CW 1 mW laser is focused to about a 1 mm spot, the power density is about 0.127 W/cm^2. The same CW 1 mW laser focused to 50 micron spot will give power of 50 W/cm^2. If a higher power 500 mW CW laser is used, and is focused to a 1 mm spot, a power density of 63 W/cm^2 is reached and the same laser focused to 50 μm will lead to the power density of $2.5*10^4$ W/cm^2. Thus, typical power densities for CW lasers are in 0.1 W/cm^2 to $2.5*10^4$ W/cm^2 range. With the use of Q-Switched lasers for sample excitation, the power densities are much different. For example, at an average power of 1 mW, and pulse duration of 10 nanoseconds ($10*10^{-9}$ s) and repetition rate of 100 kHz, the momentary power may be as high as 1 W and the corresponding power density at a 1 mm spot is 127 W/cm^2. When the same laser is used with an average power of 500 mW, and is focused to 50 μm spot size, the momentary power may reach, e.g., $2.5*10^7$ W/cm2.

The lens system may further include a scanning system 116, illustrated as including a scanning mirror 118 and a fixed mirror 120, that is used to scan the illumination spot across the width of the surface of the sample 101 as an illumination line 122, that is illustrated as being orientated along the X direction. The scanning speed/frequency of scanning system 116 may be adjusted depending on the scan resolution and sensor read-out speed. For example, the frequency may be, e.g., between 50-100 Hz range, but may vary in a range of 1 Hz to 10 kHz or more. The scanning mirror 118 moves to scan the illumination spot across the surface of the sample 101 and may be, e.g., a (swinging) galvanometric mirror or a rotating

polygonal mirror. FIG. 2A, by way of example, illustrates a top view of the surface of the sample 101 with an illumination spot 124, produced by illumination beam 114 (FIG. 1) that is scanned across the width of the sample, as indicated by arrows 125. As illustrated, by lines 121 in FIG. 1, the scanning system 116 scans the illumination beam 114 across the sample 101 within a plane, which creates a non-zero angle of incidence α1, with respect to surface normal N. Thus, the illumination line 122 is incident on the surface of the sample 101 at a non-normal angle of incidence. It should be understood that the illumination line 122 is additionally scanned across the surface of the sample 101 by the stage 104 (FIG. 1) moving the sample 101 along the Y direction, as illustrated by arrow 123, so that the illumination line 122 may be incident on all positions on the surface of the sample 101.

It should be understood that FIG. 1 illustrates one configuration of the narrow band illumination source 110 and associated optics, including scanning system 116, but that other configurations may be used if desired. For example, while the use of fixed mirror 120 is advantageous to simplify system alignment, if desired, the fixed mirror 120 may be removed from scanning system 116, with the light source 110, lens 112, and scanning mirror 118 repositioned so that the illumination beam 114 illuminates the sample 101 directly, without the need for the redirecting mirror 120. Moreover, it should be understood that the optics 112 may focus the illumination beam 114 into an illumination spot 124 on a surface of the sample 101. If the illumination beam 114 is focused at a sample plane, which is coincident with the surface of the sample 101, the illumination spot may become slightly defocused as the illumination beam moves along the illumination line 122, but the signal intensity variations caused by the defocusing can be compensated by signal processing within computer 150. Alternatively, by way of example, the optics 112 may collimate the illumination beam 114. If desired, the collimated illumination beam 114 may be focused on the surface of the sample using an optional F-theta lens 117, shown with dotted lines in FIG. 1. Moreover, if desired, the collimated illumination beam 114 may be incident on the surface of the sample 101 as the illumination spot without being focused, with an associated loss of resolution and excitation conditions.

By scanning the illumination spot 124 across the sample 101 to produce the illumination line 122, a high power density of the incident light may be maintained. Consequently, the illumination beam from light source 110 imparts energy into the material of the sample via "photo-excitation" thereby producing photoluminescence light emitted from the sample along the illumination line 122. Additionally, surface defects on the sample 101, such as scratches, particles, epitaxial growth defects, e.g., stacking faults or mounds, may scatter the illumination beam 114 as it is scanned along the illumination line 122.

As illustrated, by lines 121 in FIG. 1, the scanning system 116 scans the illumination beam 114 across the sample 101 within a plane, which creates a non-zero angle of incidence α1, with respect to surface normal N. Thus, the illumination line 122 is incident on the surface of the sample 101 at a non-normal angle of incidence.

The optical metrology device 100 includes a detector 130 that receives light from the surface of the sample 101 along a detector path 131 that has a non-zero angle α3 with respect to surface normal N. Thus, as illustrated in FIG. 1, the detector 130 has viewing angle α3 that is different than the angle of incidence α1 of the illumination line 122. As a result, the specular reflection of the illumination beam 114 from the surface of the sample 101 does not enter the detector path 131.

Typically, the photoluminescence signal is a few orders weaker than the reflected radiation signal. With the use of the angle of incidence α1 and the viewing angle α3, the optical metrology device 100 permits the illumination beam 114 to reflect from the specular surface of the sample 101 without interfering with the photoluminescence signal received by the detector 130, thereby avoiding the need for filtering the reflection of the illumination beam 114. Moreover, because the illumination beam 114 is not filtered, the detector 130 may receive light scattered by surface defects without receiving illumination beam 114, i.e., enabling dark field observations. It should be understood that the photoluminescence light produced by the sample 101 in response to excitation by the illumination beam 114 will have a different wavelength(s) than the illumination beam 114 itself. Accordingly, the wavelengths from the photoluminescence light and the scattered light can be dispersed into different spectral channels. Consequently, the optical metrology device 100 may be used for simultaneous detection of surface topographical defects and photoluminescence. Additionally, with the use of the scanning system 116, the light source 110 may function as a line illumination source without loss of power density or illumination uniformity along the line if a cylindrical lens or cylindrical mirror were used.

The detector 130 includes optics 132, a spectrometer 134, and a sensor 136 that includes a two-dimensional CCD or CMOS sensor array. The light collected along the detector path 131, e.g., photoluminescence light or scattered light, is collected by the fore optics 132, then passes through a narrow entrance slit aperture in the spectrometer 134. The field of view of the spectrometer 134 is limited by the entrance slit, which matches the orientation of the illumination line 122. Thus, the entrance slit of the detector 130, or to be more exact, the spectrometer 134, is aligned with the illumination line 122 and overlaying broadband illumination line 142 (discussed below), i.e. the entrance slit and illumination lines 122 and 142 all belong to the same plane, while illumination line 122 and 142 are overlaid on top of each other and the entrance slit to the detector 130 is parallel to the illumination lines 122 and 142. The spectrometer 134 disperses the spectrum of the received light and the sensor 136 at the exit of the spectrometer 134 records with a two dimensional (2D) sensor array and produces a resulting image frame, with a first dimension of the sensor array representing the spatial position along the illumination line 122 and the second dimension of the sensor array representing spectral information. The spectrometer 134 separates the wavelengths of emitted photoluminescence light and separates the scattered light along one dimension of the 2D sensor array, while the position along the illumination line 122 is recorded by the second dimension of the 2D sensor array. For example, one point along the illumination line 122 may emit a maximum photoluminescence at 460.3 nm, while another point on the illumination line 122 may emit a maximum photoluminescence at 460.8 nm. Thus, the spectrometer 134 separates the wavelengths of the emitted photoluminescence light to perform spectral photoluminescence imaging.

The metrology device 100 further includes a second light source 140, which may be, e.g., a broadband illumination source, such as a halogen light source, that includes wavelengths of light that differ from the wavelengths used by the first light source 110 or the wavelengths of photoluminescence light emitted by the sample 101 in response to excitation by the illumination beam 114. The broadband radiation source (sometimes referred to as a "white" light source) is formed into the illumination line 142 which is aligned with and overlays the illumination line 122 on the surface of the sample 101. As illustrated, the illumination line 142 may be

produced, e.g., using a series of optical fibers **144** (only one of which is illustrated as coupled to the light source **140**). By way of example, the second light source **140** with the series of optical fibers **144** may be a Lightline product manufactured by Schott North America, Inc. The light from the multiple optical fibers **144** is formed into a nearly collimated line-like beam with a cylindrical lens **146**. FIG. **2B** illustrates a top view of the sample **101** with the illumination line **142** from the second light source **140**.

As illustrated in FIG. **1**, the broadband light from light source **140** illuminates the surface of the sample **101** along a plain, illustrated by lines **141** that is at a non-zero angle of incidence $\alpha 2$, with respect to surface normal N. Thus, the illumination line **142** is incident on the surface of the sample **101** at a non-normal angle of incidence $\alpha 2$. It should be understood that the illumination line **142** is additionally scanned across the surface of the sample **101** (along with overlaid illumination line **122**) by stage **104** (FIG. **1**), as illustrated by arrow **145** in FIG. **2B**, so that the illumination line **142** may be incident on all positions on the surface of the sample **101**. The angle of incidence $\alpha 2$ is different from the angle of incidence $\alpha 1$ and has a sign that is different from the sign of angle $\alpha 1$, i.e., the illumination line **142** is incident on the surface of the sample from an opposite direction as the illumination line **122**, and has a different angle of incidence. The angle of incidence $\alpha 2$ of the illumination line **142**, however, is equal, but opposite in value, as the viewing angle $\alpha 3$ of the detector path **131**, i.e., viewing angle $\alpha 2 = -\alpha 3$. Thus, the detector **130** viewing angle is tuned to the incident angle of the illumination line **142** and as a result, the specular reflection of the broadband light along illumination line **142** is also aligned with the field-of-view of the spectrometer **134**. Thus, both the illumination line **122** produced by light source **110** and the illumination line **142** produced by the light source **140** are received by the detector. The spectrometer **134** separates the wavelengths of the specular reflection of the broadband illumination along the illumination line **142** into one dimension of the 2D sensor array, while the position along the illumination line **142** (and the illumination line **122**) is represented by the second dimension of the 2D sensor array.

The broadband light source **140** may use wavelengths of light that are different than the wavelength(s) used by the first light source **110** and wavelength(s) of the photoluminescence light emitted by the sample **101** so that the spectrometer **134** may separate the wavelengths from the reflected broadband light from the wavelengths of the scattered light and the wavelengths of the photoluminescence lights. Accordingly, the first light source **110** and second light source **140** may be used with the detector **130** to simultaneously detect the spectral information with respect to position along with illumination lines **122** and **142** for the photoluminescence light caused by the excitation of illumination beam **114**, the dark field scattering of the illumination beam **114**, as well as the bright field reflectance from the light source **140**. By way of example, the optical metrology device **100** may use a range of wavelengths between 400-1,000 nm (i.e. 600 nm range), based on the wavelengths of the narrow band light source **110**, the broadband light source **140**, and the emitted photoluminescence light. The detector **130** may separate the received light into, e.g., 1200 wavelengths, i.e., number of pixels in the spectral dimension of the sensor array, and thus, the detector **130** may have a spectral resolution of 0.5 nm. Of course, if desired, other spectral resolutions may be used, as well as wavelengths of light or ranges of wavelengths of light, as well as the number of wavelengths detected by detector **130**.

Moreover, the broadband light that is specularly reflected from the surface of the sample **101** is directed to the detector

130 without any need for mechanical repositioning of the detector **130**, therefore the detector **130** can collect the surface reflectance, scattering and photoluminescence signals concurrently or in a quick succession without any delay for mechanical repositioning of any apparatus optics subcomponents. Of course, if desired, the first light source **110** and second light source **140** may be used in quick succession so that the detector **130** does not simultaneously receive light from both illumination lines **122** and **142**.

The sample **101** is held on a linear stage **104** that can translate the sample **101** in a direction that is different than the orientation of the illumination lines **122** and **142**. For example, the orientation of the illumination lines **122** and **142** may be in a direction (e.g., the X-direction) that is orthogonal to the direction of travel of the linear stage **104** (e.g., the Y-direction). The stage **104** translates the sample **101** to place the illumination lines **122** and **142** at multiple positions across the sample **101** (as illustrated by arrows **123** and **145** in FIGS. **2A** and **2B**) and the spectral imaging of the illumination lines **122** and **142** is repeated at each new position. The process of imaging and moving the sample **101** is repeated to scan the illumination lines **122** and **142** across the sample **101** thereby producing a series of 2D image frames. If desired, the stage **104** may move the sample **101** in steps or move the sample **101** continuously so that data acquisition is performed continuously (e.g., with a high frequency scan of the illumination spot **124**), without the Y-axis motion stopping at each line. For example, when a high frequency scan (e.g., 500 Hz) of the illumination spot **124** is used with a relatively low speed stage motion along the Y-axis and low speed collection of image frames (e.g., 100 Hz), the illumination beam **114** is scanned over the illumination line **122** several times for each given image frame, e.g., five times in the given example, which provides for improved signal averaging. The speed of the stage motion along Y axis may be expressed in millimeters per second and depends on the desired resolution along the Y direction. For example, when the Y speed is 20 mm/s and the frame rate is 100 frames per second, the Y resolution is 20 mm/s divided by 100/s equals 0.2 mm.

Thus, in one data capture operation, the optical metrology device **100** is able to collect concurrently the spectral photoluminescence and spectral scattered radiation and spectral reflected radiation signals from the line-illuminated portion of the sample **101**, and may move in a single axis and repeatedly perform the data capture operation to acquire data for the entire sample surface. In one embodiment the data for the entire sample surface is obtained by moving the sample **101** underneath of the illumination lines **122** and **142** with a linear stage in the Y-direction. In another embodiment, however, the data can be collected by rotating the sample **101** underneath of the illumination lines **122** and **142** with a rotary stage in Θ (angle) direction, illustrated in FIG. **1** with a dotted arrow. In both embodiments, the sample **101** is moved in one axis only, either Y or Θ (both are not required), resulting with a high speed measurement. In comparison, conventional systems acquire data from a single illumination spot and must move the sample in two axes to acquire data for the entire sample surface. Thus, the optical metrology device **100** uses a single unidirectional stage, as opposed to the conventional two linear or linear and rotary stage systems. Moreover, data acquisition is accelerated because of the elimination of required stage motion along the X-axis.

It should be understood that the motion between the illumination lines **122** and **142** and sample **101** is relative, and thus, if desired, the stage **104** may be held stationary and the illumination lines **122** and **142** may be moved (laterally in the Y direction or rotated in the Θ direction using a stage to move,

e.g., the light sources and associated optics with respect to the sample **101**, or other appropriate means.

The plurality of image frames produced by the detector **130** as the sample **101** is moved and spectral information from the line-illuminated portions of the sample **101** is acquired may be received by a computer **150**, which may store the plurality of image frames as three dimensional (3D) data cube. The 3D data cube includes two dimensions that are spatial (e.g., one dimension is the position along the illumination lines **122** and **142** (X axis) and the other dimension is the position of the line scanned across the sample (Y axis)) and a third dimension represents the spectral information. The detector **130** is coupled to provide the image data to the computer **150**, which includes a processor **152** with memory **154**, as well as a user interface including e.g., a display **158** and input devices **160**. A non-transitory computer-usable medium **162** having computer-readable program code embodied may be used by the computer **150** for causing the processor to control the metrology device **100** and to perform the functions including the analysis described herein. The data structures and software code for automatically implementing one or more acts described in this detailed description can be implemented by one of ordinary skill in the art in light of the present disclosure and stored, e.g., on a computer readable storage medium **162**, which may be any device or medium that can store code and/or data for use by a computer system such as processor **152**. The computer-usable medium **162** may be, but is not limited to, magnetic and optical storage devices such as disk drives, magnetic tape, compact discs, and DVDs (digital versatile discs or digital video discs). A communication port **164** may also be used to receive instructions that are used to program the computer **150** to perform any one or more of the functions described herein and may represent any type of communication connection, such as to the internet or any other computer network. Additionally, the functions described herein may be embodied in whole or in part within the circuitry of an application specific integrated circuit (ASIC) or a programmable logic device (PLD), and the functions may be embodied in a computer understandable descriptor language which may be used to create an ASIC or PLD that operates as herein described.

By way of example, the computer **150** may use the photoluminescence signals received from the detector **130** for each position on the surface of the sample **101** as stored in the 3D data cube and generate a photoluminescence image (or map) of the sample **101**. The photoluminescence image may be, e.g., a map of signal intensity of the photoluminescence signal. Inspection of the photoluminescence intensity image may be used for process control to assure that all portions of the sample **101** meet desired specifications. For example, where the sample **101** contains manufactured light emitting diodes (LEDs) chips, inspection of the photoluminescence data, e.g., in the form of a photoluminescence intensity image, can be used to assure each LED will have appropriate brightness. Similarly, the photoluminescence intensity image may be used for defect segmentation and predicting yield losses based on presence of localized low photoluminescence signals, which can lead to out-of-specification device at the Back-End of Line. If desired, the photoluminescence signal may be processed to produce other images or maps. For example, a Peak Lambda image may be produced to show the distribution of Peak Lambda over the sample surface, where Peak Lambda is the wavelength at which any given point in the image or map has maximum photoluminescence. Thus, for example, one point on the sample surface may emit maximum photoluminescence at 460.3 nm, while another point on the surface of the same sample may emit a maximum photoluminescence at 460.8 nm, which can be clearly seen with a Peak Lambda image. With the use of the spectral photoluminescence imaging, the different wavelengths of photoluminescence light emitted by the sample may be identified. Accordingly, the optical metrology device **100** may be used for process control to assure that all points on the sample surface emit photoluminescence within a predefined wavelength range. Additionally or alternatively, the photoluminescence signal can be transformed into a Full-Width-Half Maximum (FWHM) image, which shows the FWHM value for each Peak Lambda at any given point on the sample. The FWHM image, by way of example, may be used to assure that light emitting diodes (LEDs) that are manufactured with the sample emit light within predefined-width (band) spectral range. The photoluminescence signal may be processed to produce images of the sample **101** other than the photoluminescence intensity, Peak Lambda and FWHM images. For example, the photoluminescence signals may be processed or analyzed to produce different qualities, such as, e.g., a map of photoluminescence intensity at a given fixed wavelength, which is different than the maximum photoluminescence intensity map. Moreover, images or maps of interest may be produced by combining sets of images, such as those discussed, e.g., by pixel-by-pixel multiplication. Thus, the photoluminescence signal may be processed to produce other desired images of the sample **101** based on the recorded photoluminescence signals or analyzed in other ways for process control during manufacture of the sample.

Additionally, the computer **150** may process the received reflected broadband signal to determine a characteristic of the sample **101** at multiple positions and produce a map of that characteristic. For example, layer thickness may be calculated based on the spectral response associated with reflection of the broadband light, and thus, the received reflected broadband signal may be used to determine thickness for points on the sample surface and an epilayer thickness image (or map) may be produced. Thus, the optical metrology device **100** may be used to monitor the epitaxial layer thickness at any given point on the surface of the sample, which may be used to assure that the measured thickness is within predefined range for a given epitaxial growth process. Additionally, using the received scattered light, the computer **150** may produce a darkfield image of the surface of the sample **101**, thereby exposing surface defects, which may be related scratches, particles, epitaxial growth defects, e.g., stacking faults or mounds, etc.

FIGS. **3A** and **3B** illustrate a perspective view and side view, respectively, of the dark channel observation of scattered light by optical metrology device **100**. As illustrated, the light source **110** produces illumination line **122** on the surface of the sample **101** using the optics **112** and scanning system **116**, including scanning mirror **118** and fixed mirror **120**. If the sample were defect free, light would be specularly reflected by the surface of the sample **101**, as illustrated by lines **125**, and would not be detected by the camera sensor **136**. When a surface defect **126** is present on the sample **101**, a portion of the illumination beam **114** is scattered when the illumination beam **114** is scanned over the defect **126**. The scattered light along the detector path **131** received by the detector **130** and enters the spectrometer **134** through the slit aperture. The field of view of the spectrometer **134** is limited by a slit aperture, and therefore, the sensor **136** only images the illumination line **122**. The specular reflection of the illumination beam **114** is not received by the spectrometer **134**. The spectrometer **134** normally separates light into wavelength bins in the spectral dimension of the 2D sensor array. The scattered light, however, originates from the narrow band

light source **110** and, thus, the scattered received by detector **130** is deflected by the spectrometer **134** into the bin(s) corresponding to the wavelength(s) of the light source **110**, which is recorded by the sensor **136**. The performance of the scattered light channel may be further altered by adding light polarizer and analyzer into the optical path of the narrow band illumination beam **114**. By way of example, a beam polarizer **119** may optionally be placed downstream of the light source **110**, e.g., between the lens **112** and mirror **118**, and the analyzer **133** may be combined with the fore optics **132**.

FIGS. **4A** and **4B** illustrate a perspective view and side view, respectively, of the bright field reflectance observation by optical metrology device **100**, omitting the light source **110** and associated optics for clarity. The broadband light source **140** illuminates the sample **101** along the illumination line **142** line extending across the width of the sample **101** along an orientation that matches the orientation of the entrance slit of the spectrometer **134**. As a result, the light from the light source **140** that is specularly reflected from the surface of the sample **101** enters the spectrometer **134** through the slit aperture. Within the spectrometer **134**, the broadband light is separated (binned) into a series of wavelengths, which are recorded by 2D sensor array in the sensor **136**, with one dimension of the 2D sensor array representing the spectral information and the other dimension representing the spatial information along the illumination line **142**. The arrangement of the broadband light source **140**, thus, is a bright field mode of operation in which an illumination line **142**, which may be the width of the sample **101**, is spectrally imaged. The use of a non-normal angle of incidence for the bright field observation advantageous simplifies uniform illumination and spectroscopic imaging of the sample **101** along illumination line **142**.

FIGS. **5A** and **5B** illustrate a perspective view and side view, respectively, of the excitation of the sample **101** with the scanning illumination beam **114** and the emitted photoluminescence light collection by optical metrology device **100**. Similar to FIGS. **3A** and **3B** above, the light source **110** produces illumination line **122** on the surface of the sample **101** using the optics **112** and scanning system **116**, which may include scanning mirror **118** and fixed mirror **120**. As discussed above, fixed mirror **120** may be removed or replaced and/or a F-Theta lens may be used. The light from illumination beam **114** that is specularly reflected is illustrated by lines **125**. Another portion of the light from illumination beam **114**, however, enters the sample **101** and is absorbed. The absorbed energy generates electron-hole pairs, which upon recombination emit photoluminescence light along the excitation line, i.e., illumination line **122**. The generated photoluminescence light emitted from the excitation line exits the sample **101** at multiple directions with near Lambertian characteristics. FIG. **6**, by way of example, illustrates the incident illumination beam **114** and the Lambertian characteristic of the emitted photoluminescence light (the specularly reflected light is not illustrated in FIG. **6**). In addition, because the illumination beam **114** is scanned across the width of the sample **101** along illumination line **122**, the photoluminescence light is emitted along the excitation direction, as illustrated in FIG. **5A**. The emitted photoluminescence light along the detector path **131** is received through the slit aperture of the spectrometer **134**, where the light is deflected by the spectrometer **134** into the bin(s) corresponding to the wavelength(s) of the photoluminescence light, which is recorded by the sensor **136**.

FIGS. **7** and **8** illustrate a side view (along the Y-Z plane) and a front view (along the X-Z plane), respectively, illustrating the simultaneous collection of dark field scattered radiation, bright field reflectance radiation and photoluminescence

light by the optical metrology device **100**. As illustrated, the illumination beam **114** generates scattered light **115**, and excites photoluminescence light **117**, that are received by the spectrometer **134**, along with the reflected broadband light **143**.

FIG. **9**, by way of example, illustrates the signal separation of the three spectral channels (dark field scattered radiation, bright field reflectance radiation, and photoluminescence light) imaged by the 2D sensor array of sensor detector **136**. As illustrated, the 2D sensor array includes a first dimension (the X axis in FIG. **9**) representing the spatial information along the illumination lines **122** and **142**, with the other dimension representing the spectral information, i.e., wavelength λ, with respect to the signal intensity. In FIG. **9**, the scattered laser beam signal is illustrated by peaks **202**, the photoluminescence signal is illustrated by peaks **204**, and the reflected broadband beam signal is illustrated by peaks **206**.

Thus, as illustrated in FIGS. **7**, **8**, and **9**, the detector **130** can simultaneously record the photoluminescence light generated in the sample **101** in response to excitation by the illumination beam **114** and a bright field reflection of the broadband light **143**. If desired, the detector **130** may further record a dark field scattering of the illumination beam **114** by defects on the sample so that, if desired, three separate signals are simultaneously imaged. The three signals may be recorded simultaneously along the entire width of the sample **101** in a macroscopic mode, as opposed to being recorded point-by point or within a narrow field of view in a microscopic as is conventionally performed. Moreover, one detector **130** is used to collect all three signals, so that there is no spatial or time shifts between the three signals. A spectrometer **134** separates the signals into three different spectral information channels, i.e., signals are spectrally separated that are recorded in different wavelength bins (sensor pixels) with the 2D sensor array sensor of the detector **130**. It should be understood that the image frame illustrated in FIG. **9** is for one position of the illumination lines **122** and **142** along the Y axis in FIG. **1** and that as the stage **104** moves the sample **101** in the Y direction to scan the illumination lines **122** and **142** across the sample, the sensor **136** will produce a plurality of image frames for each position of the illumination lines **122** and **142** along the Y axis in FIG. **1**.

FIG. **10** is a flow chart illustrating a method of optical metrology data from a number of light sources. As illustrated, a surface of a sample is illuminated at a first angle of incidence with a first light source along a first illumination line having an orientation in a first direction (**302**). The sample emits photoluminescence light from the first illumination line in response to excitation caused by light from the first light source. By way of example, as discussed above, the sample may be illuminated with an illumination beam produced, e.g., using a narrow band light source **110**, and that is scanned across the sample to produce the first illumination line. The surface of the sample is illuminated at a second angle of incidence with a second light source along a second illumination line having an orientation in the first direction and that overlays the first illumination line (**304**). The second angle of incidence is different than the first angle of incidence, and the second light source is a broadband light source. The broadband light is reflected from the surface of the sample. The photoluminescence light emitted by the sample along the first illumination line and specular reflection of broadband light from the second illumination line is detected with a two-dimensional array having a first dimension representing spatial information corresponding to position along the first illumination line and the second illumination line and a second dimension representing spectral information (**306**). The

specular reflection of light from the first light source along the first illumination line may not be detected. The first illumination line and the second illumination line, which are overlaid, are moved across the surface of the sample in a second direction that is different than the first direction (**308**). For example, the first direction and second direction may be orthogonal. Movement of the first illumination line and the second illumination line may be caused by a linear stage or a rotary stage moving the sample **101** with respect to the illumination lines. If desired, movement of the first illumination line and the second illumination line may be caused by a stage moving the first illumination line and the second illumination line with respect to the sample **101**, e.g., by moving the light sources and associated optics with respect to the sample **101** which may be held stationary. A three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information is produced using detected photoluminescence light and detected specular reflection of broadband light as the first illumination line and the second illumination line are moved across the surface of the sample (**310**).

Additionally, as discussed above, a portion of the light from the first light source may be scattered off surface defects on the sample as scattered light and the scattered light may be detected with the two-dimensional array, where the three dimensional data cube additionally includes the detected scattered light. Using the scattered light in the three dimensional data cube, a surface defect image of the surface of the sample may be produced. Additionally, a photoluminescence image of the surface of the sample may be produced using the detected photoluminescence light in the three dimensional data cube. For example, the photoluminescence image of the surface of the sample may be, e.g., a photoluminescence intensity image, photoluminescence Peak Lambda image, or a photoluminescence Full-Width-Half Maximum (FWHM) image. Additionally, a characteristic of the sample may be determined for a plurality of positions on the surface of the sample using the detected specular reflection of broadband light in the three dimensional data cube, and an image of the surface of the sample may be generated using the characteristic of the sample for the plurality of positions. For example, the epilayer thickness of the sample **101** may be determined at a plurality of locations on the surface of the sample **101** and an epilayer thickness image (or map) may be produced. As discussed above, the data from the three dimensional data cube may be analyzed for process control during manufacture of the sample.

FIG. **11**, by way of example, illustrates a side view of an optical metrology device **100'**, that is similar to the optical metrology device **100** illustrated in FIG. **7**, except that the narrow band illumination beam **114'** is illustrated as being incident from the same side of normal N as the broadband illumination **141'**. Thus, while the narrow band illumination beam **114'** and broadband illumination **141'** are incident on the surface of the sample **101** from the same side of normal N, they use different angles of incidence, so that the specular reflection **125'** of the narrow band illumination **114'** is not along the detector path **131**, thereby enabling dark field mode measurement. As can be seen in FIG. **11**, the angle of incidence of the illumination beam **114'** is greater than the angle of incidence of the broadband illumination **141'**, with respect to normal N, but this is not strictly required. FIG. **12**, by way of example, is similar to FIG. **11**, and illustrates an optical metrology device **100"** that is configured so that the narrow band illumination beam **114"** has a smaller angle of incidence compared to the broadband illumination **141'**, with respect to normal N, while the specular reflection **125"** of the narrow

band illumination **114"** is still not along the detector path **131**, thereby enabling dark field mode measurement.

Although specific embodiments are provided herein for instructional purposes, the described embodiments are not limiting. Various adaptations and modifications may be made without departing from the scope of the present discloser. For example, a rotary stage may be used in place of a linear stage for scanning the illumination lines **122** and **142** across the surface of the sample **101**. Moreover, the scanning system **116** may be modified to eliminate, e.g., the fixed mirror, or an F-theta lens may be used for focusing the illumination beam **114** on the surface of the sample **101**. Other modifications and variations are possible, and therefore, the spirit and scope of the appended claims should not be limited to the foregoing description.

What is claimed is:

1. An apparatus comprising:
a light source that produces an illumination beam;
an optical system that receives the illumination beam and produces an illumination spot on a surface of the sample, wherein all wavelengths in the illumination beam are simultaneously combined in the illumination spot;
a scanning system that scans the illumination spot to form an illumination line across the sample, wherein the scanning system scans the illumination beam in a plane that is at a non-normal angle of incidence on the sample, and wherein the sample emits photoluminescence light in response to excitation caused by the illumination spot along the illumination line;
a stage for providing relative movement between the illumination line and the sample;
a detector that images the photoluminescence light emitted along the illumination line on a two-dimensional array with a first dimension representing spatial information along the illumination line and a second dimension represent spectral information of the photoluminescence light, wherein the detector produces an image frame representing the photoluminescence light emitted along the illumination line, and wherein the detector produces a plurality of image frames for the illumination line on the surface of the sample as the stage produces relative movement between the illumination line and the sample; and
a processor coupled to the detector to receive the plurality of image frames and generates a photoluminescence image of the surface of the sample.

2. The apparatus of claim **1**, wherein the processor generates the photoluminescence image of the sample that is one of a photoluminescence intensity image, photoluminescence Peak Lambda image, and a photoluminescence Full-Width-Half Maximum (FWHM) image.

3. The apparatus of claim **1**, wherein the stage moves the sample in a first direction, the illumination line being orientated in a second direction that is orthogonal to the first direction.

4. The apparatus of claim **1**, wherein the first direction is a linear direction or a rotational direction.

5. The apparatus of claim **1**, wherein the scanning system that scans the illumination spot to form the illumination line on the surface of the sample comprises a galvanometric mirror or a polygonal mirror.

6. The apparatus of claim **1**, wherein a portion of the illumination spot is scattered off surface defects on the sample as the illumination spot is scanned across the surface of the sample producing scatter signals along the illumination line, the detector receives the scatter signals and images the scatter signals along the illumination line on the two-dimen-

sional array with the first dimension representing spatial information along the illumination line and the second dimension represent spectral information of the scatter signals, wherein the plurality of image frames further comprise the scatter signals, and wherein the processor generates a surface defect image of the sample using the scatter signals from the plurality of image frames.

7. The apparatus of claim 1, wherein the illumination beam is a first illumination beam, the illumination line is a first illumination line, and the non-normal angle of incidence is a first non-normal angle of incidence, the apparatus further comprising:

a broadband light source that produces broadband light;

a lens that focuses the broadband light into a second illumination line on the surface of the sample, the second illumination line overlays and is aligned with the first illumination line and is incident on the sample at a second non-normal angle of incidence that is different than the first non-normal angle of incidence, wherein the second illumination line is reflected by the sample to produce reflected light;

the detector receives the reflected light and images the reflected light along the second illumination line on the two-dimensional array with the first dimension representing spatial information along the second illumination line and the second dimension represent spectral information of the reflected light, wherein the plurality of image frames further comprise the reflected light.

8. The apparatus of claim 7, wherein the processor determines a characteristic of the sample for a plurality of positions on the surface of the sample using the recorded reflected light from the plurality of image frames and generates a second image of the surface of the sample using the characteristic of the sample for a plurality of positions.

9. The apparatus of claim 7, wherein the second non-normal angle of incidence is from an opposite direction than the first non-normal angle of incidence.

10. The apparatus of claim 7, wherein the detector receives specularly reflected broadband light.

11. An apparatus comprising:

a stage for providing relative movement between the illumination line and the sample in a first direction;

a first illumination source that produces a first light beam;

a first lens system that causes the first light beam to be incident on a surface of the sample as a first illumination line orientated along a second direction that is different than the first direction, the first illumination line being incident on the sample at a first angle of incidence, wherein the sample emits photoluminescence light in response to excitation caused by the first light beam along the first illumination line;

a broadband illumination source that produces broadband light;

a second lens system that focuses the broadband light onto the sample as a second illumination line orientated along the second direction and that is overlaid on the first illumination line on the surface of the sample, the broadband light being incident on the sample at a second angle of incidence that is different than the first angle of incidence;

a detector that receives reflected broadband light from the surface of the sample from the second illumination line and receives the photoluminescence light emitted by the sample along the first illumination line, wherein the detector images the reflected broadband light and the photoluminescence light on a two-dimensional array with a first dimension representing spatial information

along the second direction and a second dimension representing spectral information of the reflected broadband light and the photoluminescence light and produces an image frame in response, wherein the detector produces a plurality of image frames for a plurality of positions of the first illumination line and the second illumination line that are overlaid on the surface of the sample as the stage moves the sample in the first direction; and

a processor coupled to the detector to receive the plurality of image frames and stores the plurality of image frames as a three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information.

12. The apparatus of claim 11, wherein a portion of the first light beam is scattered off surface defects on the sample producing scatter signals along the first illumination line, the detector receives the scatter signals and images the scatter signals along the first illumination line on the two-dimensional array, wherein the plurality of image frames further comprise the scatter signals.

13. The apparatus of claim 12, wherein the processor generates a surface defect image of the sample using the scatter signals from the plurality of image frames.

14. The apparatus of claim 11, wherein the processor generates a photoluminescence image of the sample using the photoluminescence light from the plurality of image frames that is one of a photoluminescence intensity image, photoluminescence Peak Lambda image, and a photoluminescence Full-Width-Half Maximum (FWHM) image.

15. The apparatus of claim 11, wherein the processor determines a characteristic of the sample for a plurality of positions on the surface of the sample using the reflected light from the plurality of image frames and generates an image of the surface of the sample using the characteristic of the sample for a plurality of positions.

16. The apparatus of claim 11, wherein the second lens system comprises a scanning mirror to scan the first light across the sample in the second direction to form the first illumination line.

17. The apparatus of claim 16, wherein the scanning mirror comprises a galvanometric mirror or a polygonal mirror.

18. The apparatus of claim 11, wherein the first illumination line and the second illumination line are produced concurrently.

19. The apparatus of claim 11, wherein the first illumination line and the second illumination line are produced sequentially.

20. The apparatus of claim 11, wherein the first direction is a linear direction or a rotational direction.

21. A method comprising:

illuminating a surface of a sample at a first angle of incidence with a first light source along a first illumination line having an orientation in a first direction, wherein the sample emits photoluminescence light from the first illumination line in response to excitation caused by light from the first light source;

illuminating the surface of the sample at a second angle of incidence with a second light source along a second illumination line having an orientation in the first direction and that overlays the first illumination line, wherein the second angle of incidence is different than the first angle of incidence, and wherein the second light source is a broadband light source, wherein broadband light is reflected from the surface of the sample;

detecting the photoluminescence light emitted by the sample along the first illumination line and specular reflection of broadband light from the second illumination line with a two-dimensional array having a first dimension representing spatial information corresponding to position along the first illumination line and the second illumination line and a second dimension representing spectral information;

moving the first illumination line and the second illumination line across the surface of the sample in a second direction that is different than the first direction; and

producing a three dimensional data cube with two dimensions representing spatial information of the surface of the sample and a third dimension representing spectral information using detected photoluminescence light and detected specular reflection of broadband light as the first illumination line and the second illumination line are moved across the surface of the sample.

22. The method of claim **21**, wherein a portion of the light from the first light source is scattered off surface defects on the sample as scattered light, the method further comprising detecting the scattered light with the two-dimensional array, and the three dimensional data cube is further produced using the detected scattered light.

23. The method of claim **22**, further comprising producing a surface defect image of the surface of the sample using the scattered light in the three dimensional data cube.

24. The method of claim **21**, wherein specular reflection of light from the first light source along the first illumination line is not detected.

25. The method of claim **21**, wherein illuminating the surface of the sample at the first angle of incidence with the first light source along the first illumination line comprises generating an illumination beam and scanning the illumination beam across the surface of the sample to produce the first illumination line.

26. The method of claim **21**, further comprising producing a photoluminescence image of the surface of the sample using the detected photoluminescence light in the three dimensional data cube.

27. The method of claim **26**, wherein the photoluminescence image of the surface of the sample comprises at least one of a photoluminescence intensity image, photoluminescence Peak Lambda image, and a photoluminescence Full-Width-Half Maximum (FWHM) image.

28. The method of claim **21**, further comprising determining a characteristic of the sample for a plurality of positions on the surface of the sample using the detected specular reflection of broadband light in the three dimensional data cube, and generating an image of the surface of the sample using the characteristic of the sample for the plurality of positions.

29. The method of claim **21**, further comprising analyzing data from the three dimensional data cube for process control during manufacture of the sample.

30. The method of claim **21**, wherein the first direction is a linear direction or a rotational direction.

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